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Performance improvement of high repetition rate electro-optical cavity-dumped $Nd:GdVO_4$ laser

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Abstract We improved the electro-optical cavity-dumped $Nd:GdVO_4$ laser performance at high repetition rates by employing continuous-grown $GdVO_4$/$Nd:GdVO_4$ composite crystal under 879 nm diode-laser pumping. A constant 3.8 ns duration pulsed laser was obtained and the repetition rate could reach up to 100 kHz with a maximum average output power of 13.1 W and a slope efficiency of 56.4%, corresponding to a peak power of 34.4 kW.

Keywords Diode-pumped laser · Electro-optical Q-switched · Cavity-dumped

1 Introduction

Pulsed lasers in nanosecond region are widely used in many applications such as material processing, laser ranging, remote sensing, and so on [1–3]. Diode pumped solid-state Q-switched oscillator is a common way to realize nanosecond pulsed lasers with a merit of high efficiency and good beam quality. Under the conventional Q-switched operation, however, it is difficult to obtain short nanosecond pulse at high repetition rates, because its pulse width is variable depending on the laser medium's gain, the operating repetition rate and the transmission of the output coupler. In comparison, a cavity-dumping structure can realize short constant pulse duration, which is determined by the cavity length and the Q-switch apparatus's switching time. In 2004, M. Siebold et al. reported a constant 7 ns pulse duration cavity-dumping $Nd:YVO_4$ laser with the maximum average output power of 5.3 W and repetition of 80 kHz [4]. In 2006, L. McDonagh et al. presented a 41 W, 6 ns cavity-dumped $Nd:YVO_4$ laser at 100 kHz by 888 nm diode-laser pumping [5]. In 2007, C. Stolzenburg et al. reported a cavity-dumped intracavity-frequency-doubled 515 nm Yb:YAG thin disk laser, and the maximum average output power was 102 W at 50 kHz with a pulse width of 300 ns [6]. Compared with $Nd:YVO_4$, $Nd:GdVO_4$ crystal has better thermal properties. The thermal conductivity along the direction of ⟨110⟩ is about two times higher than that of $Nd:YVO_4$ [7]. Although the stimulated emission cross-section of $Nd:GdVO_4$ at 1.06 μm is only half of that to $Nd:YVO_4$ [8], the cavity-dumping pulse duration is not affected for it is independent of the gain in the laser medium. So it is significant to investigate the cavity-dumped properties of $Nd:GdVO_4$ laser. However, to the best of our knowledge, no work on it has been reported.

Previously, we investigated the performance of cavity-dumped 1063 nm $Nd:GdVO_4$ laser under 808 nm pumping in a linear cavity. It realized a constant 5.5 ns pulse duration, and the highest repetition rate could reach 50 kHz with the maximum average output power was 5.1 W, corresponding to a peak power of 18.5 kW. In order to scale up the laser power and improve the beam quality, it is essential to take measures to control the thermal effect. Direct pumping by 879 nm LD has been approved to be an efficient scheme because it reduces the quantum defect ratio by 0.07 to 0.17 compared to 808 nm pumping. Composite crystal is another effective way to relieve the thermal lens effect, which can be attributed to the undoped cap of the composite crystal acting as an effective heat diffuser [9]. In this paper, we presented a high repetition rate, high peak power electro-optical cavity-dumping $Nd:GdVO_4$ laser, using continuous-grown $GdVO_4$/$Nd:GdVO_4$ composite crystal under 879 nm

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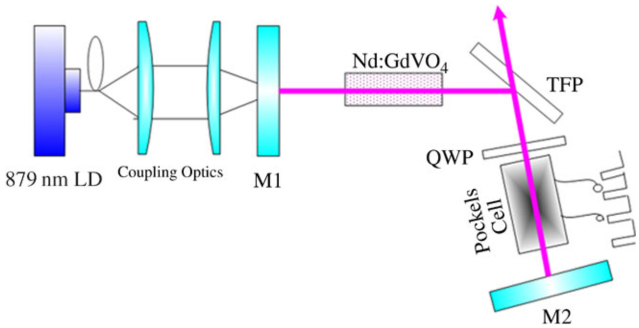


Fig. 1 Cavity-dumped $GdVO_4$/Nd:$GdVO_4$ laser under 879 nm LD pumping

LD pumping. Compared with the maximum average output power of 41 W and 102 W demonstrated by [5] and [6] with dual-end-pumping and thin disk configuration, respectively, we developed a simple and high efficiency V-type cavity with single-end-pumping. The pulse width remained constant at 3.8 ± 0.2 ns, and at repetition rates of 100 kHz, 50 kHz, and 10 kHz, the corresponding peak powers were 34.4 kW, 65.9 kW, and 252.6 kW, respectively. The maximum output power of 13.3 W was reached at the optimum repetition rate of 80 kHz.

2 Experimental setup

The experimental setup of the electro-optical cavity-dumped Nd:$GdVO_4$ laser is shown in Fig. 1. In our experiments, we employed a V-type cavity instead of linear cavity because of its higher extinction ratio and lower losses in s-wave oscillation mode. The 879 nm LD pumping source was fiber coupled with a core diameter of 400 μm and a numerical aperture of 0.22. Two achromatic lenses were employed to re-image the pump beam into the crystal with a spot diameter of about 640 μm. The cavity length was 175 mm. The plano-plano mirrors M1 and M2 were both coated for high reflection (HR) at 1063 nm. M1 was also coated antireflection at 879 nm. The doped part of the composite $GdVO_4$/Nd:$GdVO_4$ crystal had a dimension of $3 \times 3 \times 8$ mm^3 and a Nd^{3+}-doped concentration of 0.3 at.%. The undoped cap of the composite crystal was 2 mm long. The RTP Pockels cell was used as the Q-switch and its driver's rise and fall times were both 3.5 ns. A thin-film polarizer (TFP) and a quarter wave plate (QWP) were employed in the experiment.

3 Analysis and simulations

In the cavity-dumped process, the QWP axes were oriented at 45° to s and p polarizations. Then the incident s polarization from TFP would be rotated into p polarization in double pass. Therefore, when no voltage was applied to the RTP Pockels cell, the p-polarized mode would be outputted through the TFP. During this period the cavity was in high loss, so the laser was held off under threshold and the inversion population would be accumulated. Once $\lambda/4$ voltage was imposed on the Pockels cell, the polarization would not be changed through QWP and Pockels cell in double pass. This resulted in the low loss of the cavity and the intracavity laser pulse would be built up between the two HR end mirrors. After the voltage was removed, the laser pulse would be dumped out from the TFP. So the oscillation mode was in s polarization and the output mode was in p polarization.

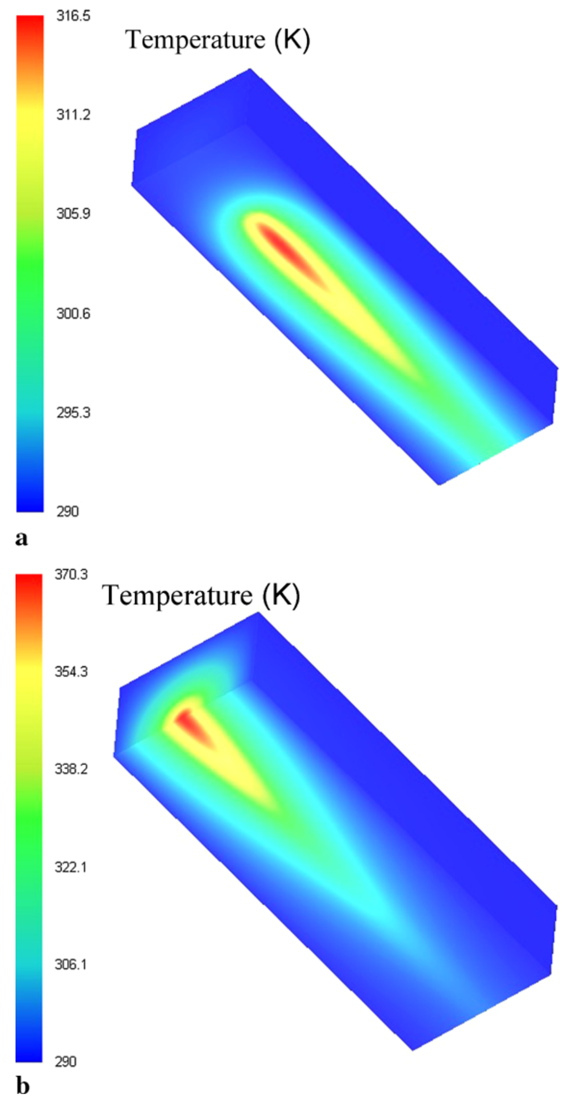


Fig. 2 (**a**) Temperature distribution of $GdVO_4$/Nd:$GdVO_4$ under 879 nm pumping; (**b**) temperature distribution of Nd:$GdVO_4$ under 808 nm pumping

In order to investigate the performance improvement of composite $GdVO_4$/Nd:$GdVO_4$ crystal under 879 nm pumping, we simulated its temperature distributions according to the experimental conditions by LASCAD software, and the

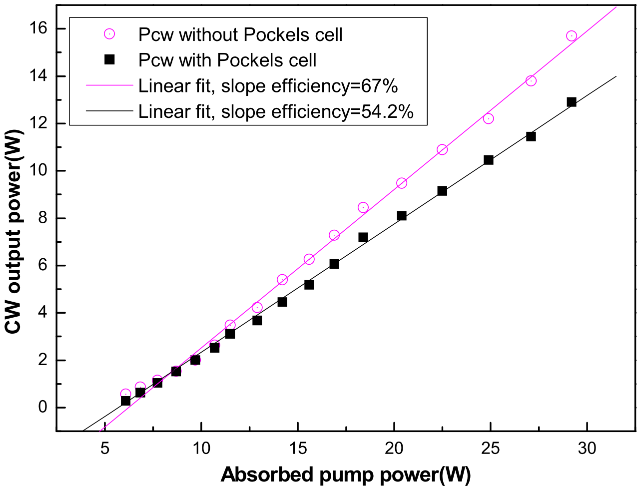
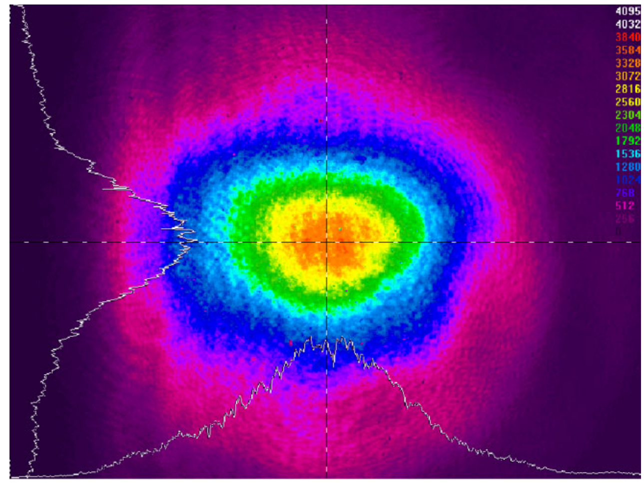


Fig. 3 CW operation of $GdVO_4$/Nd:$GdVO_4$ laser under 879 nm pumping

result was compared with that of conventional Nd:$GdVO_4$ crystal under 808 nm pumping. The total dimensions of composite crystal were $3 \times 3 \times 10\ mm^3$, of which the undoped cap was 2 mm long. The conventional crystal dimensions were $3 \times 3 \times 8\ mm^3$. The absorbed pump power was set at 30 W. Figure 2 shows the simulated results, the highest temperature of the conventional crystal is 370.3 K in comparison, that of the composite crystal is 316.5 K, and the peak value appears in the interior of the crystal instead of the external pumped surface. These indicated that the composite crystal under 879 nm pumping suffered much lower heat load and lighter thermal lens effect, so it could scale up the laser power with better beam quality.



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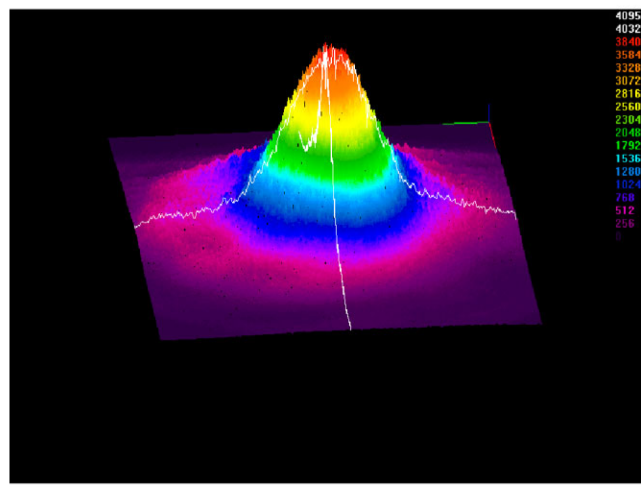

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Fig. 4 Laser beam profile at cw output power of 15.7 W. (**a**) 2-D distribution; (**b**) 3-D distribution

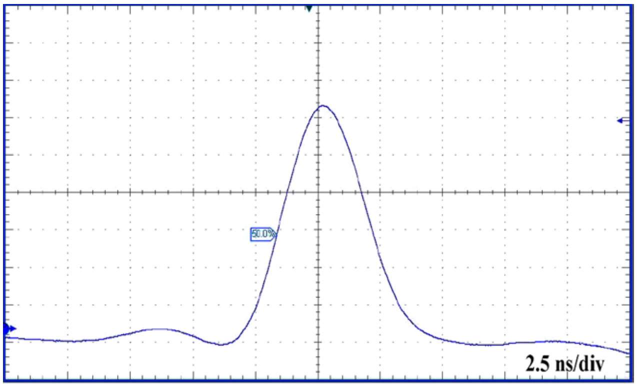
4 Experimental results and discussions

Firstly, we investigated the continuous-wave (CW) $GdVO_4$/ Nd:$GdVO_4$ laser properties under 879 nm pumping. Continuous adjustment of output coupling was realized by rotating the QWP, the coupling transmissivity $T(\theta)$ as a function of the rotated angle θ against the zero retardation point was expressed as $T(\theta) = \sin^2(2\theta)$. The maximum output power was realized at $\theta = 19°$, corresponding to an output transmissivity of 37.9%. Figure 3 depicts the output power versus absorbed pump power with and without the Pockels cell inserted into the cavity. Without the Pockels cell, the maximum output power of 15.7 W was realized at the absorbed pump power of 29.2 W, corresponding to a slope efficiency of 67%. With the Pockels cell, in comparison, the maximum output power decreased to 12.9 W and the slope efficiency decreased by 12.8% to 54.2%. The large declination can be attributed to the insert loss of RTP Pockels cell. The single-pass loss factor of the Pockels cell δ_{pc} can be determined by the following equation [10]:

$$\eta_s = \frac{\nu}{\nu_p} \frac{T}{2\delta} \frac{P_{ab}}{P_{ab} - P_{th}} \tag{1}$$

where η_s is the slope efficiency, P_{ab} is the absorbed pump power, P_{th} is the threshold pump power, T is the output transmissivity, δ is the cavity single-pass loss factor, ν is the oscillation photon frequency and ν_p is the pump photon frequency. According to the experimental data, the value δ_{pc} is calculated to be 0.066. Although the output power did not saturate yet, we did not increase the pump power higher than 30 W in order to avoid fracture of the crystal. The 2D and 3D laser beam intensity distributions at the maximum output power of 15.7 W were recorded by LBA300 (Spiricon Inc.) and they were shown in Fig. 4, from which we can see that the beam profile is of good quality.

A high-speed Si-detector (DET210/M, Thorlabs Inc.) and a digital oscillograph (DPO 7104, Tektronix Inc.) were used



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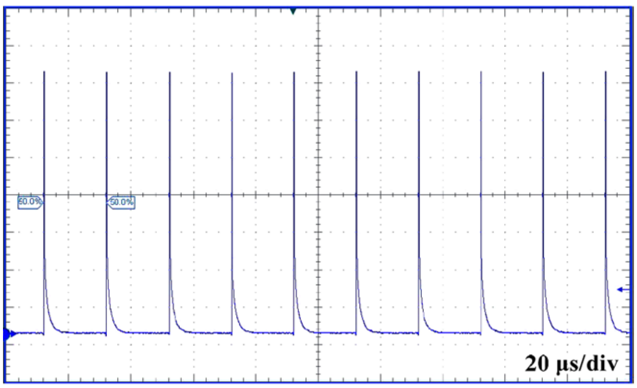

b

Fig. 5 (**a**) An oscilloscope trace of 3.8 ns pulse; (**b**) pulse train trace at 50 kHz

to detect the pulse signal and measure the pulse width, respectively. Under cavity-dumped operation, a constant pulse duration of 3.8 ± 0.2 ns was realized, and the corresponding pulse shape is illustrated in Fig. 5(a). The repetition rates can reach up to 100 kHz, but the pulse trains began to jitter above 80 kHz for the gain in the laser medium to each pulse was reduced at higher repetition rates. Figure 5(b) shows the pulse series at 50 kHz with rather good stability, and the pulse-to-pulse energy instability was less than 0.31%.

Figure 6 presents the average output power versus absorbed pump power at different repetition rates. The maximum average output powers were 13.1 W, 12.5 W, and 9.6 W with optical conversion efficiencies of 44.9%, 42.8%, and 32.9% at 100 kHz, 50 kHz, and 10 kHz, respectively. The slope efficiency at 100 kHz was 56.4%. At 10 kHz, the output power was inclined to saturate at the absorbed pump power of 29.2 W for the serious thermal effect.

The average output power and peak power as functions of repetition rate at an absorbed pump power of 29.2 W is shown in Fig. 7. The average output power increased with the increase of the repetition rate and the maximum output power of 13.3 W was reached at the optimum repetition rate of 80 kHz. This characteristic repetition rate is defined by the pumping rate and the fluorescence lifetime, which

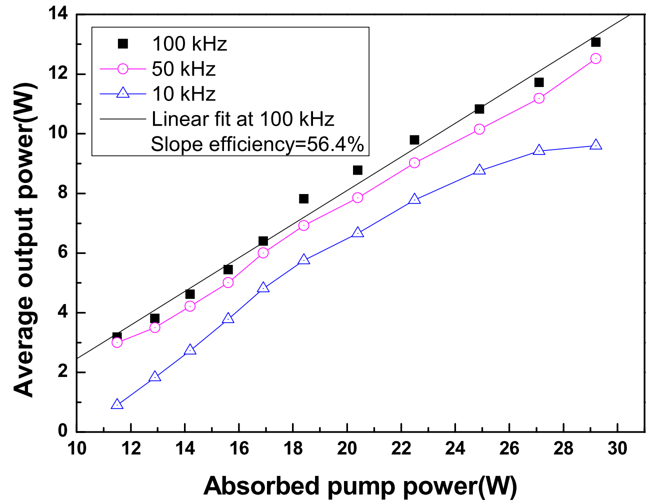

Fig. 6 Average output power versus absorbed pump power

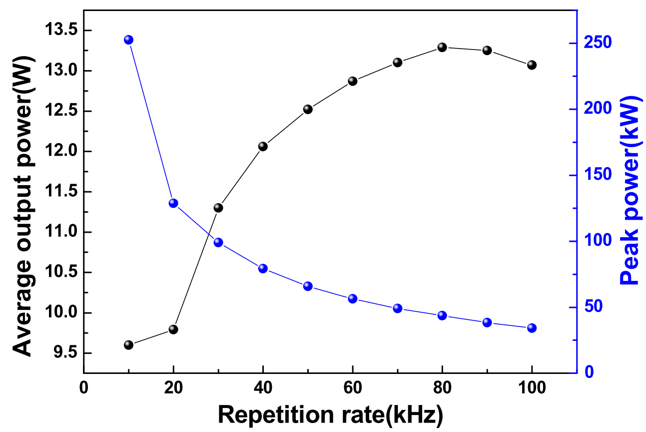

Fig. 7 Average output power and peak power versus repetition rate at an absorbed pump power of 29.2 W

determines the recovery time to reestablish population inversion in the laser medium [4]. The build-up time of the laser increased almost linearly with the repetition rates, so the output power declined beyond the maximum repetition rate of 80 kHz, which was attributed to the increase number of round trips in the cavity for the build-up of the intracavity photon pulse, and therefore suffered more losses. The peak power decreased almost exponentially with the increase of the repetition rate, and the peak powers at 10 kHz, 50 kHz and 100 kHz were 252.6 kW, 65.9 kW and 34.4 kW, respectively.

5 Conclusion

We demonstrated a high repetition rate, high peak power electro-optical cavity-dumped 1063 nm laser by employing continuous-grown $GdVO_4$/$Nd:GdVO_4$ composite crystal under 879 nm diode-laser pumping. A constant 3.8 ns pulse duration was realized. The peak powers at 10 kHz, 50 kHz and 100 kHz were 252.6 kW, 65.9 kW and 34.4 kW, respectively. The maximum output power of 13.3 W was reached at the optimum repetition rate of 80 kHz.

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